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Position and size of the electron beam in the high-energy electron beam ion trap

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Abstract

In the last decade, many spectroscopic studies have been performed using the electron beam ion trap. Often these measurements rely on the electron beam as an effective slit, yet until now, no systematic study of the position and size of the electron beam under various operating conditions has been made. Here, we present a thorough study of the electron beam's position and size (and thus the electron density) as affected by various operating parameters, and give optimal parameter ranges for operating the device as a spectroscopic source. It is shown that the diameter is constant as the energy is varied, which is important for accurate cross-section measurements. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: EBIT; Spectroscopic measurements; Helmholtz coils; Bucking coil current

1. Introduction

The electron beam ion trap (EBIT) is a device designed for the spectroscopic study of highly charged ions [1]. The ions are trapped radially by the space charge of the electron beam and axially by voltages applied to three collinear drift tubes [2]. The electron beam is directed through the trapping region and radially compressed by the strong magnetic field of a pair of super-conducting Helmholtz magnets. There it collisionally strips electrons from the atoms and ions. By adjusting the energy of the electron beam, ionization to a selected charge state can be achieved. Slotted apertures in the center drift tube allow for the observation of photons from various atomic processes through X-ray and optical windows.

The electron beam's size and position in the trap is key to much of the spectroscopy performed on an EBIT. Its narrow width allows spectroscopic instrumentation (both in the X-ray and optical regimes) to operate using the beam as an effective slit. While some types of spectroscopic measurements require no slit, such as those performed with a Ge or Si(Li) solid state X-ray pulse-height analysis system, other high-resolution spectroscopy techniques

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implemented on an EBIT, such as those using flat crystals [3], focusing crystals in the von Hámos or DuMond geometry [4,5], grating spectrometers in the EUV through visible regions, and optical prism spectrographs [6] require a narrow entrance slit. In these instruments the size of the slit is one of the limiting parameters to the resolution. This is exemplified, for instance, in the ion temperature measurement of Mg^{11+} where, using a flat crystal spectrometer, a nominal resolving power of 30 000 was achieved to infer an ion temperature of 246 eV [7]. To achieve this sort of resolution it is required that the slit width be small, so that the source broadening remains insignificant as compared to other line broadening factors (e.g., Doppler, natural line width) under study. It is, therefore, important to know the slit width (i.e., electron beam diameter) accurately. In addition to the beam's size, the position of the beam with respect to the diffracting element (crystal, grating, prism) is a determining factor in the position of the image on the detector. A shift in the position of the beam in EBIT during a measurement would be reflected in a corresponding spatial shift and a possible smearing of the image of an observed spectral line.

The electron beam current is also a critical parameter for the functioning of an EBIT. While the beam energy determines the charge state of the ions, the beam current determines the collision frequency and the ionization rates. For a given current, a smaller beam diameter means a higher electron density and, thus, faster ionization times and higher excitation rates. Though previous studies of the electron beam have been conducted on the LLNL EBITs, these were limited to measurements of the beam diameter and were performed only at one energy [1,2]. In the present study we have observed both the electron beam's position and diameter as a function of operating parameters including beam energies and currents, tuning of the steering magnets, adjustment of the bucking coil, and superconducting magnet current.

2. EBIT

A description of the physics of an electron beam ion trap has been given in Refs. [2,8–10]. For the present study, we concentrate on the geometry of the EBIT and how the beam travels through the vacuum chamber (Fig. 1). The electrons are generated at the base of EBIT with a Pierce-type electron gun. For optimal electron gun performance the value and gradient of the magnetic field must be tuned to ensure zero field across the face of the cathode [2]. A bucking coil near the cathode of the gun assures zero magnetic field at the cathode as well as providing a monotonically increasing field for the beam. Properly tuned, the bucking coil minimizes the diameter of the beam in the trap region. The potential difference between the electron

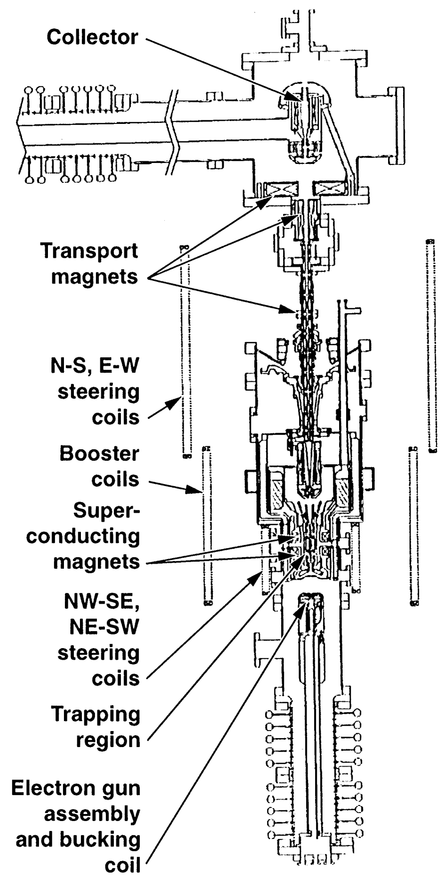

Fig. 1. Diagram of Super-EBIT. The electrons emanate at the electron gun near the bottom, travel through the trapping region, where the beam is compressed to its smallest diameter, and are guided through the vacuum chamber until they are stopped at the collector. They are guided along this path by the magnets and steering coils displayed.

gun cathode and the drift tube assembly accelerates the electrons to the drift tube region where the ions are trapped in the potential well of those three collinear electrodes. There the electron beam is compressed to its narrowest diameter by the 3.0 T field of a pair of superconducting Helmholtz coils. Slots bored in the center drift tube allow for six viewing ports arranged perpendicular to the electron beam. Several sets of steering magnets assist in directing the electron beam along the axis of the drift tubes. The beam continues through the vacuum chamber, steered by the transport magnets, until it reaches the collector region where the electrons are spread apart and stopped.

The present series of measurements was performed using a slit installed inside one of the six slots in the center drift tube of the LLNL high-energy EBIT, dubbed Super-EBIT. The slit consists of two parallel, gold-plated, platinum cylinders separated by 8 μm. The distance between the electron beam and the slit was 1.81 cm. The beam image was obtained by directly observing X-rays emitted by trapped ions with a gas-filled, position sensitive, proportional counter 99.2 cm from the slit, yielding a magnification of 55x. The X-rays traveled through a Be window on the Super-EBIT port, then through a He atmosphere from the port to the detector, which also employed a Be window. Since no diffraction elements were used, a broad band of radiation created in the trap and not absorbed by the Be windows or He atmosphere was imaged on the detector. The detected signal thus comprises X-rays from about 3–50 keV arising mainly from L- and K-shell transitions in trapped Ba and W ions, whereby the upper energy limit is given by the cut-off of the detector efficiency. The beam image at the detector was fit to a Gaussian profile such that its width and central channel position could be determined. Using these results and a knowledge of the optical system magnification the width and position of the beam were inferred and are reported here in units of microns. An absolute electron beam position was not determined, but we instead report any relative shift of the electron beam. A typical beam image overlaid with a Gaussian fit is shown in Fig. 2. The width and centroid position of the

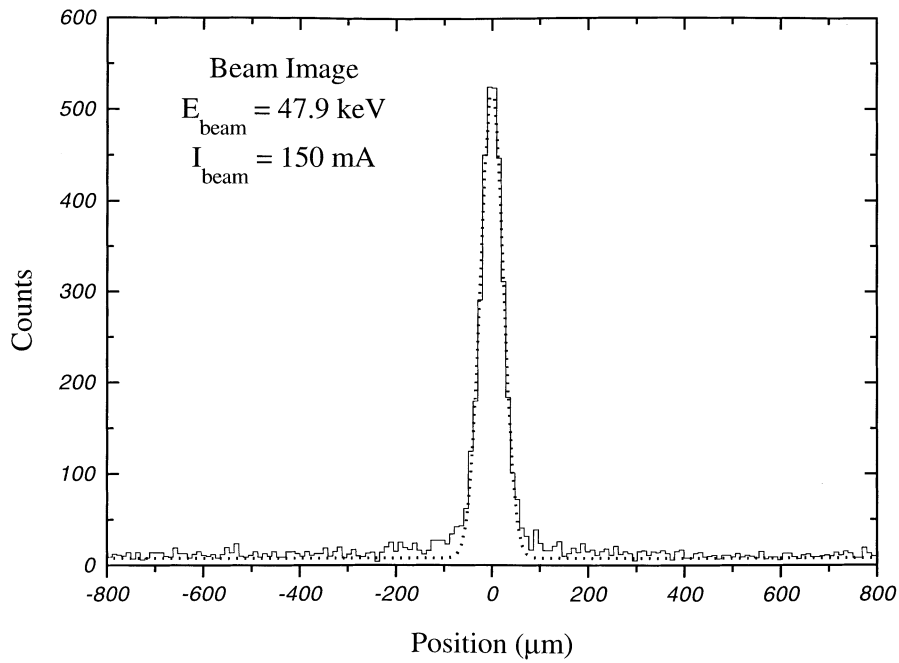

Fig. 2. Beam image obtained with a position-sensitive proportional counter. The image is overlaid with a Gaussian line profile with a FWHM of 55.5 μm, corresponding to an 80% beam radius of 42.3 ± 0.6 μm.

image were of primary interest in all of the measurements.

In addition to the current and energy of the electron beam, other parameters of interest on the Super-EBIT device are the currents applied to the superconducting Helmholtz coils, the bucking coil, and the steering magnets. The magnetic fields created by each of these elements have dynamic effects on the electron beam. While the bucking coil and Helmholtz coils affect mainly the size of the electron beam, the steering magnets directly affect the beam's position. These electromagnetic coils, which are outside of the vacuum chamber, are primarily responsible for guiding the electron beam from the electron gun, through the drift tubes, and to the collector without hitting the various apertures placed along the beam path. Their adjustment is facilitated by minimizing the amount of current picked up by these apertures, i.e., by minimizing the current loss from the high-voltage power supply responsible for floating the electron gun and the collector. There are five pairs of steering magnets designated N–S, NW–SE, E–W, NE–SW, referring to their geographical orientation about Super-EBIT, and the Booster coils, oriented in the same direction as the N–S set (see Fig. 1). The N–S and E–W magnet pairs, the largest in cross-sectional area, are located above the trapping region. Note that the electron gun is at the base of Super-EBIT, and thus below the trapping region. The next largest magnets are the booster coils which are located radially further from the trap and surround the north and south observation ports. The smallest of the magnets are the NW–SE and NE–SW oriented coil pairs. These magnets are closest to the trapping region, directly encircling the NW, NE, SE, and SW ports. (The slit through which these measurements were made is inside the NW port.) The combined effect of 10 separate steering magnets creates a complicated non-uniform magnetic field and no attempt will be made here to analyze or model it.

3. Beam radius measurement

Determination of the electron beam radius in the middle drift tube of Super-EBIT was reported by Knapp et al. in 1993. Their reported value for the beam radius, defined as the radius containing 80% of the beam current, of 33.9 ± 1.2 μm was performed at a beam energy $E_{beam} = 155$ keV and a beam current $I_{beam} = 130$ mA. In the present measurements, E_{beam} was set to 136 keV and I_{beam} was varied from a current of 90 to 230 mA. The result of the measurement of the electron beam radius as a function of I_{beam} is shown in Fig. 3a. The measured 80% beam radius increased with increasing current, ranging from 37.1 ± 1.0 μm at a current of 90 mA to 47.3 ± 0.7 μm at a current of 230 mA. This corresponds to a 60% increase in the cross-sectional area of the electron beam as the I_{beam} is increased by 160%. Since the electron

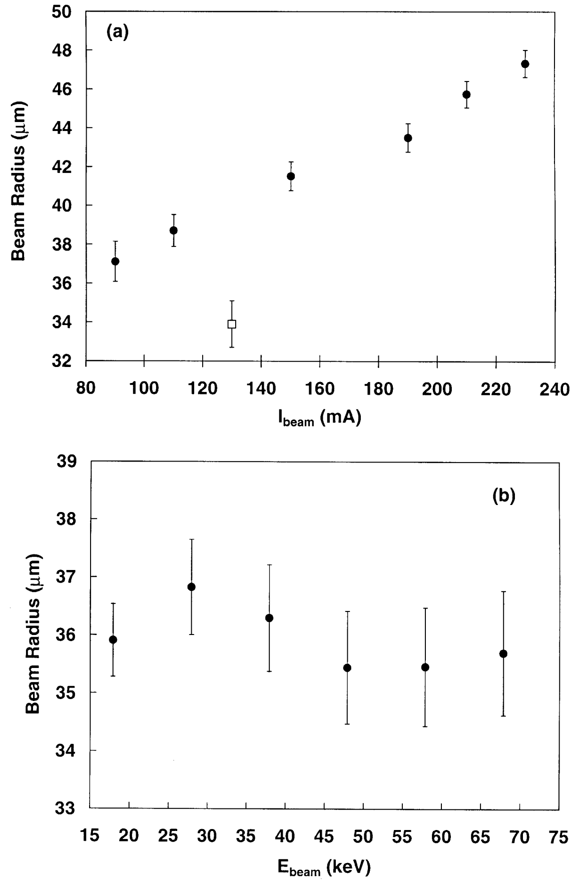

Fig. 3. Electron beam radius as a function of (a) electron beam current, I_{beam}: The energy of the beam, E_{beam}, is 136 keV. The square represents the beam radius as determined in 1993 by Knapp et al., at $E_{beam} = 155$ keV. (b) E_{beam}: $I_{beam} = 90$ mA.

density, n_e, is proportional to the I_{beam} and inversely proportional to the cross-sectional area of the electron beam, the expansion of the beam is well below that necessary to keep the n_e constant. Instead, increasing the I_{beam} increases the n_e, which, in turn, leads to a greater number of collisions with ions and faster ionization rates.

The effect of a change of E_{beam} on the beam radius is shown in Fig. 3b. I_{beam} was kept constant at 90 mA while the electron beam energy was incremented in 10 keV steps from 17.9 to 67.9 keV. From this it is seen that the beam radius remains unchanged, near 36 μm at this current, with changes in E_{beam}. Note that this beam radius is in good agreement with the 1993 measurement given above at an energy of 155 keV. Because electrons move faster at a higher E_{beam}, a constant radius means that the n_e decreases as E_{beam} is increased. In many instances the reduction in count rate due to the decreased n_e can be compensated for by the ability to achieve higher I_{beam} at greater E_{beam}.

Until now no direct, systematic observation has been reported of the effects of the bucking coil on the electron beam. Fig. 4a shows the beam radius as a function of bucking coil current. A minimum in the radius occurs for currents from 1.09 to 1.11 A with a significant increase in the radius as the coil current is outside of this range. During normal operation of Super-EBIT, optimal running conditions are determined by the minimization of loss currents in the electron beam HV power supply and by minimizing stray currents in the various apertures in the beam path. The bucking coil currents in the range 1.09–1.11 A corresponded to the optimal performance arrived at in this manner, confirming that this operational method provides the narrowest of beams. Though the value of the best current through the bucking coil will change with different running conditions, we can still be assured of a narrow beam. Comparison of two sets of data taken at different times during this experiment, labeled "Run 1" and "Run 2" in the figure, also shows that the radius is reproducible.

As mentioned, the superconducting Helmholtz coils create a strong, uniform magnetic field throughout the trapping region. It is this field which compresses the electrons so that a high-density beam is created in the trap. The beam radius, therefore, should expand as this field is decreased. Fig. 4b shows the extent of the beam compression as the current in the superconductors is varied. A dependence of the beam radius on the Helmholtz coils current is indeed seen. During normal operation of Super-EBIT, the Helmholtz coils are kept at a constant current, usually at 160 A.

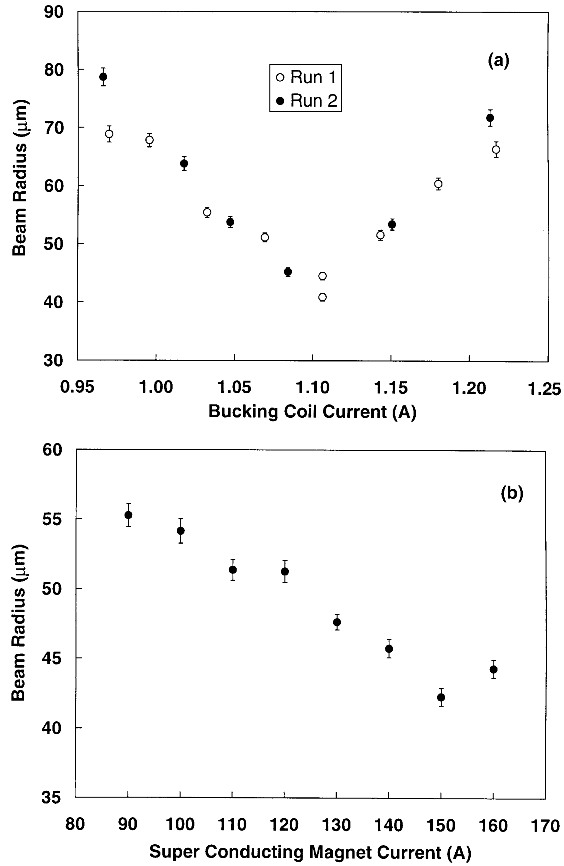

Fig. 4. Electron beam radius as a function of (a) bucking coil current: The minimum radius corresponds to the best running conditions of Super-EBIT as determined by other methods discussed in the text. (b) Superconducting Helmholtz coils current: These coils are necessary to create a high-density electron beam in the trap region.

4. Beam position measurement

Direct, detailed measurements of the stability and reproducibility of the position of the electron beam in the EBIT have not yet been reported, although spectroscopic measurements in which line positions have been measured over hundreds of hours of operation of Super-EBIT have shown a high degree of stability [11], intimating a high degree of rigidity of the beam position. The design of the slit/detector arrangement allowed this measurement to be performed simultaneously to the beam diameter measurement. Any shift in the position of the beam in the trap perpendicular to the NW port which contains the slit would appear as a shift in the central position of the beam's image in the detector.

Fig. 5a shows the effect of varying I_{beam} on the line position. As can be seen, the position of the line center is steady throughout the measurements, varying only on the order of one-half channel, or equivalently 1.1 μm. This variation is fully compatible with statistics, suggesting that the line position is unaffected by the electron beam current.

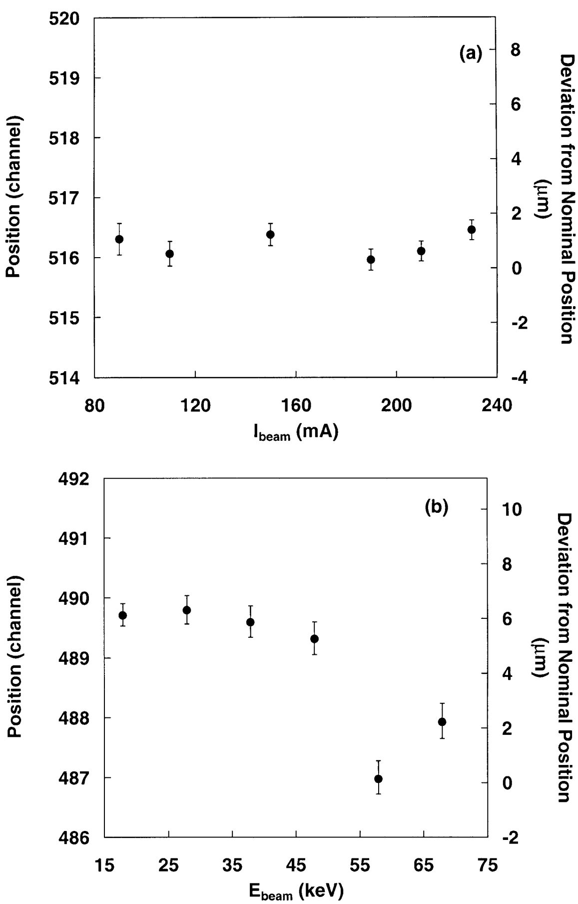

Fig. 5. Position of the electron beam as a function of (a) I_{beam} and (b) E_{beam}. One channel corresponds to about 2.2 μm.

Fig. 5b depicts the position of the beam in Super-EBIT as the energy of the beam is changed. Though not as steady as in the measurement investigating changing current, the position of the beam is essentially constant. The slight changes in the center position of the beam in the trap region (about 6 μm maximum variation) can be attributed to adjustments to other Super-EBIT parameters which were necessary to keep the electron beam from hitting the walls of the vacuum assembly. These adjustments were only necessary for the two highest energies and are more fully addressed in the following paragraph.

It was found in the study of the bucking coil that the beam diameter is strongly dependent on the proper bucking coil current. It is also evident from the plot of line position versus bucking coil current, Fig. 6a, that changing the bucking coil current has the effect of moving the electron beam. In addition to this, we show that the steering coil current can impact the beam's position in the trap. Fig. 7 displays a sample of six measurements with vastly differing steering magnet settings (here the Booster coil setting remained always the same) indicating that the beam can be moved significantly in the trapping region, up to about one beam width, by changing the current in the magnets. A closer study suggests that the NE–SW pair of magnets, i.e., the pair oriented perpendicular to the line of sight, caused most of the translation displayed here, noting that only motion perpendicular to the slit was detectable. It is also seen that a significant change in the magnetic field of the superconducting Helmholtz coils can shift the beam in the trapping region (Fig. 6b). Though it was found that the beam can be moved significantly, it is also worth noting that the position is reproducible when the magnet settings are repeated.

5. Discussion

Spectroscopic measurements on an EBIT device depend heavily on the width and stability of the

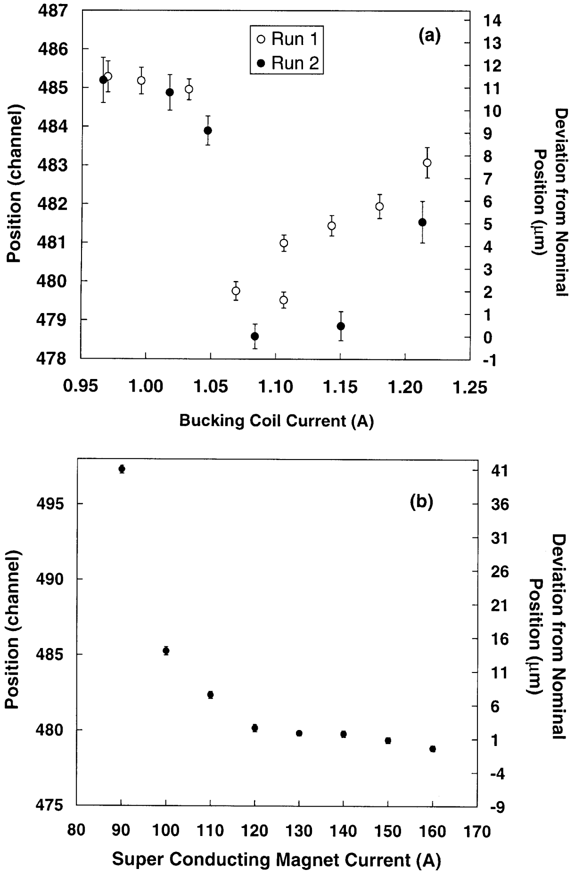

Fig. 6. Position of the electron beam as a function of (a) bucking coil current and (b) superconducting coil current. The two sets of data in (a) illustrate the reproducibility of the line position.

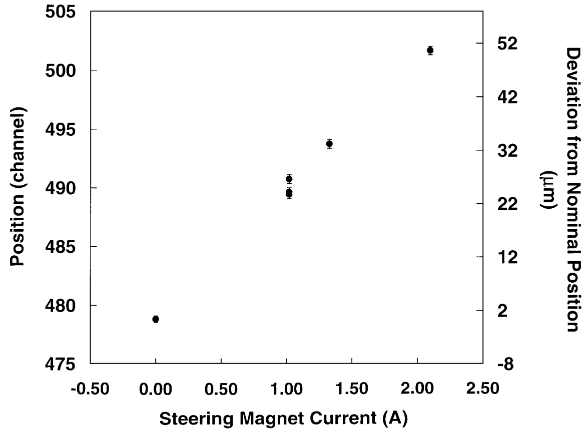

Fig. 7. Line position as a function of current in the NW–SE steering magnets. Notice the three overlapping data points at 1.0 A current. The current of the other sets of magnets are significantly different for each of these three points suggesting that it is the NW–SE set of magnets that caused the most detectable movement of the electron beam.

electron beam. These measurements show that changes in the electron beam current have only small effects on the position and diameter of the electron beam. If the need arises to change the current during a measurement, this can be done with no significant error being introduced to the data. The beam energy has a small effect on the electron beam width, but affects little the line position. This means that a change in the energy might change the spectroscopic resolution slightly (by a few percent), but no error is added in the assignment of the line position for measurements at differing energies.

Moreover, measurements of cross-sections have been made where the electron beam is repeatedly swept through a range of energies while the current remains constant. The relationship between the beam current and the beam radius is important in these measurements. Since $\varepsilon \propto \sigma n_e v_e$, where ε is the emissivity, σ is the total cross-section, n_e is the electron density, and v_e is the speed of the electrons in the beam, and $j = e n_e v_e$, where j is the current density and e is the elementary charge, comparison of cross-sections at differing energies is best performed if the current density remains constant throughout the measurements. It has been shown in the present measurements that the radius of electron beam, r, remains constant as the E_{beam} is changed and the I_{beam} remains unchanged. This means that the current density, $j = I_{\text{beam}}/\pi r^2$, is constant as the energy is swept and cross-section measurement comparisons are made easier. Note that this does not take into consideration the effects due to the ion density or the electron–ion overlap. Neither of these quantities were studied in these measurements.

It is shown here that certain adjustments to the EBIT can have significant effects on the electron beam's width and position, while at the same time it is shown that the width and position are stable and reproducible. The most dramatic change in the width of the beam comes from changing the bucking coil current. It is also shown here that the standard operational method of setting the bucking coil current does result in the smallest beam width. The position was shifted most significantly by changing the current in the steering magnets. By drastically changing the current in the steering magnets the beam was moved about 50 μm. It is important to emphasize that normal EBIT operation does not involve any adjustments to the bucking coil, steering magnets, or super-conducing magnets during the taking of data. This type of adjustment, in fact, would be detrimental to the operation of the EBIT.

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